Luminosity and longitudinal density monitoring in the LHC

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Outline

- LHC
- BSRL: Longitudinal density monitoring
- BRAN: Luminosity monitoring
  - Prototype for High-Luminosity LHC Upgrade

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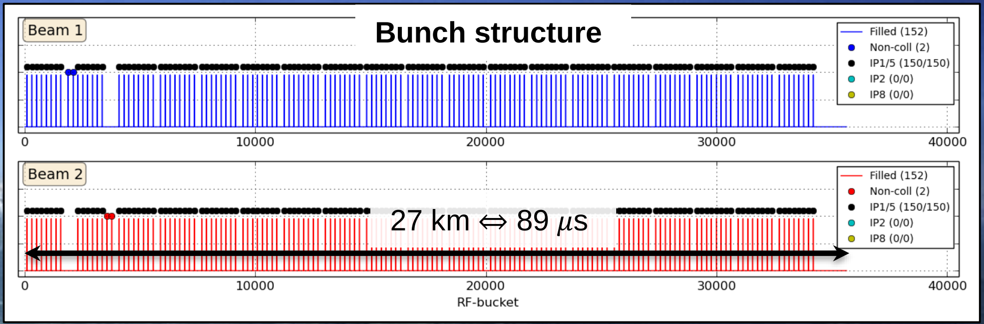
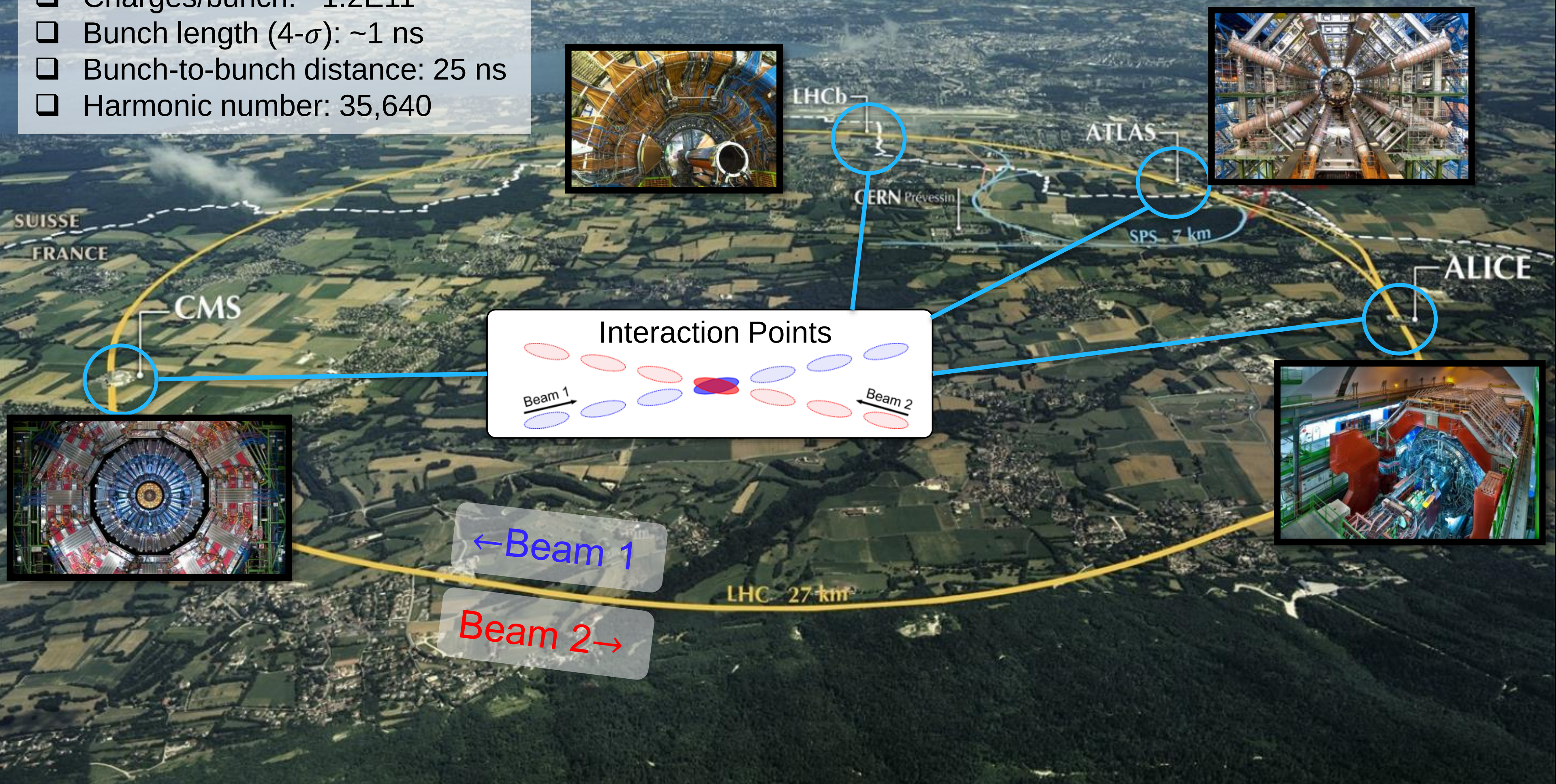
LHC

- Large Hadron Collider
- Circumference: 27 km
- Injection Energy: 450 GeV
- Flat Top Energy: 6.5 TeV
- Max bunches: 2,556
- Charges/bunch: ~1.2E11
- Bunch length (4-σ): ~1 ns
- Bunch-to-bunch distance: 25 ns
- Harmonic number: 35,640





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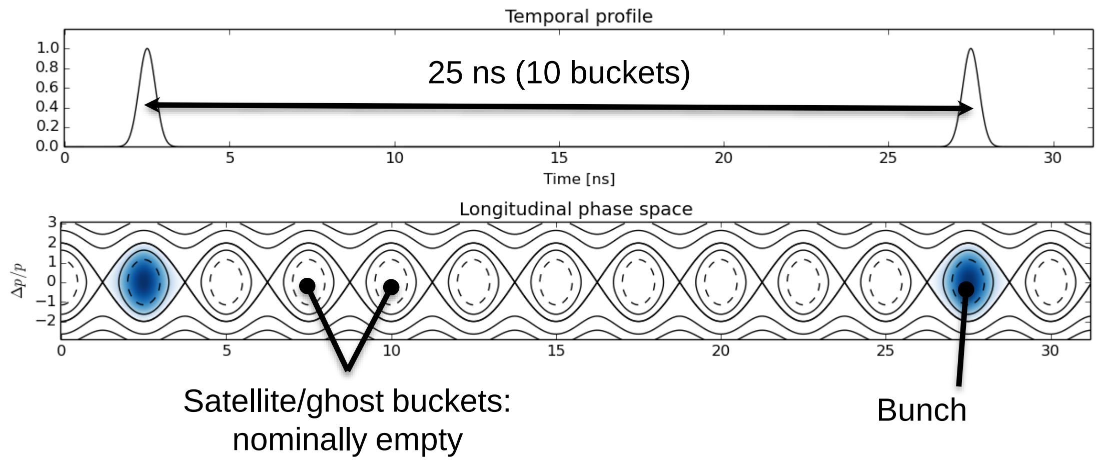
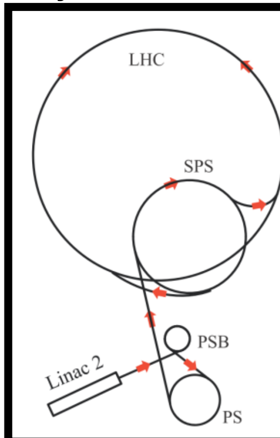
BSRL: Purpose

- ❑ The bunches are confined in “buckets”
- ❑ 35,640 buckets in total
- ❑ Minimum bunch separation: 10 buckets
- ❑ **Most of the LHC is empty**



Injector chain



- ❑ Along the LHC injector chain, a small fraction of the beam may be trapped in buckets that should be empty. These low-intensity bunches are called **“Satellite” or “Ghost” bunches** (depending on how close to the filled bucket they are)
- ❑ Satellite and ghost bunches may collide with nominal bunches at IPs → **Increased background**

Ghost charge measurement

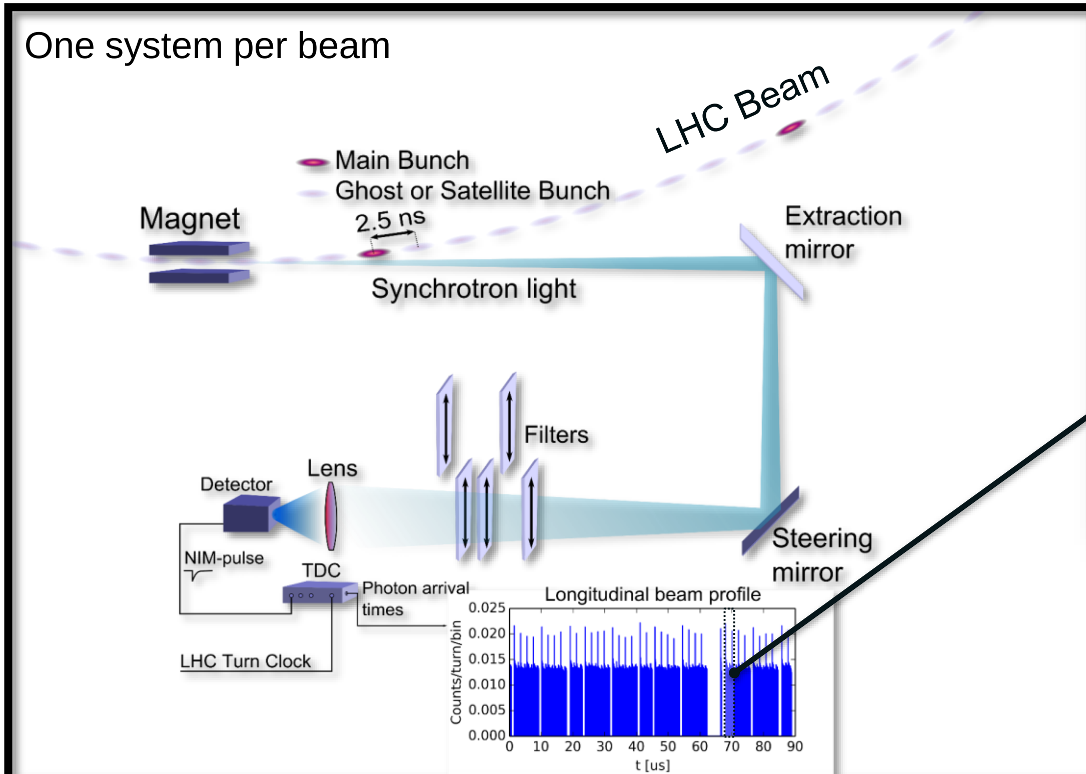
- ❑ **Luminosity calibration** requires accurate measurement of ghost charge
- ❑ Verify **injection quality**: If too much ghost charge, something is wrong…
- ❑ Determine **origin** of background signal at IPs

Challenges

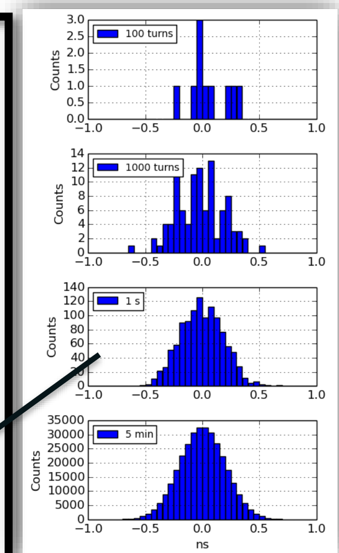
- ❑ **High dynamic range**: Individual ghost bunches are ~0.001% to 1% of nominal bunches (but sum of all is not negligible…)
- ❑ **Resolution**: Bunch $\sigma \sim 250$ ps
- ❑ LHC Beam Current Transformers cannot do this! ⇒ Main purpose of BSRL

Principle

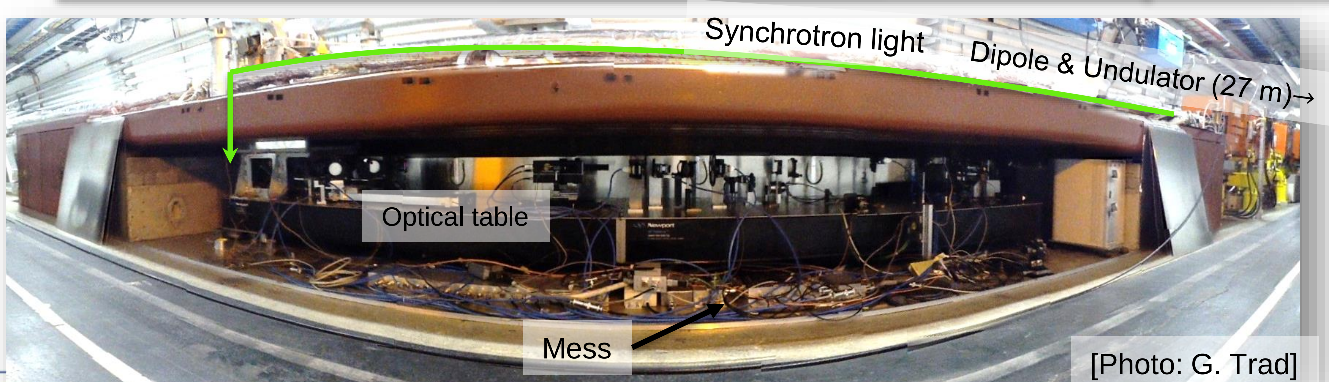
- BSRL = **B**eam **S**ynchrotron **R**adiation: **L**ongitudinal
- Synchrotron radiation ∝ Temporal beam profile
- Time-correlated single photon counting



Zoom, single bunch

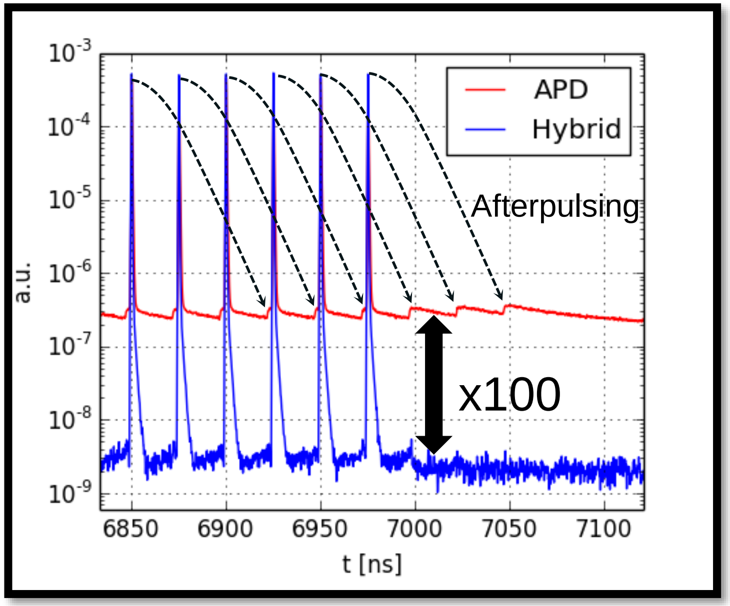


- **Resolution: 50 ps**
- 1,780,000 bins per histogram
- **5 min** integration time



Detector

- Generation 1: APD
  - 2010 - 2015
  - Single-photon avalanche diode
  - Motorized
  - Robust
  - 70 ns deadtime
  - 50 μm sensor
  - Afterpulses

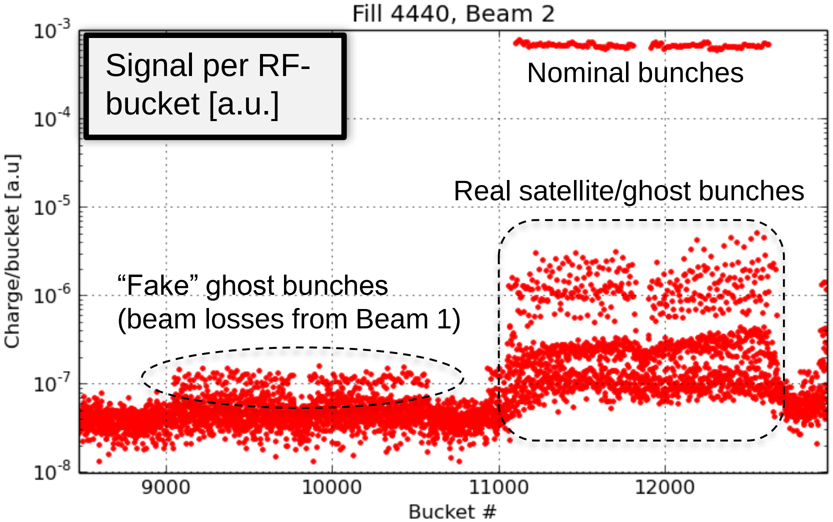


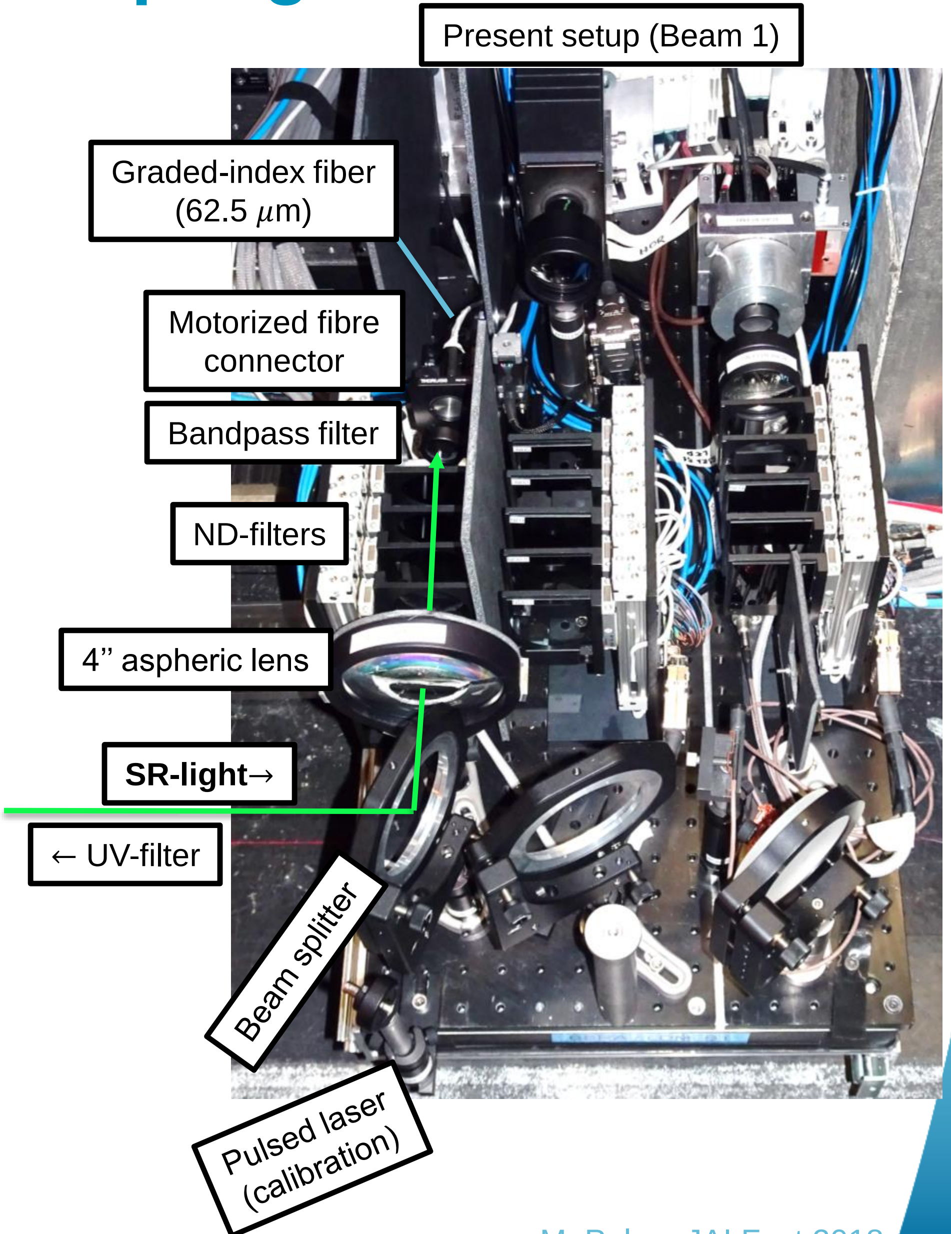
- Comparison: laser pulse train response (25 ns separation)
- APD: Limited usability due to afterpulses (drowns ghosts) and deadtime
- Hybrid: dynamic range = 5 orders of magnitude

- Generation 2: PMA Hybrid (Picoquant)
  - 2015-
  - Electron bombardment + avalanche
  - Damaged by too intense light
  - "Zero" deadtime
  - 6 mm cathode
  - No afterpulses (almost…)
  - Dark count rate <50cps

Fiber coupling

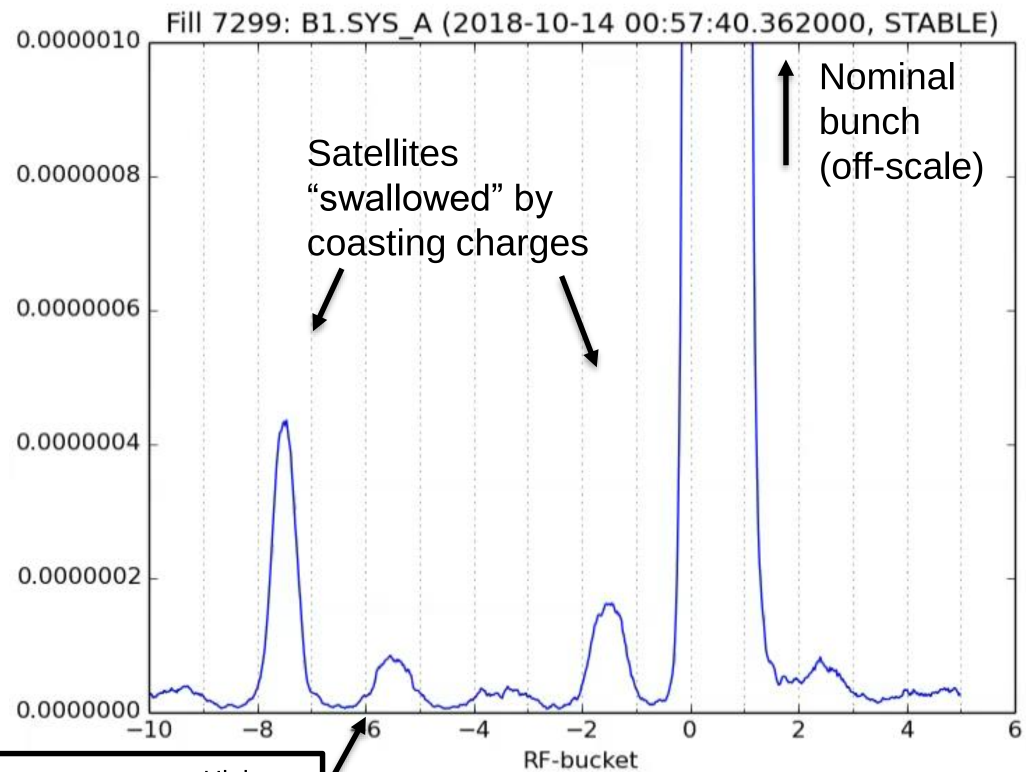
- ❑ Hybrid detector extremely sensitive
- ❑ Secondary stray particles (**beam losses**) from Beam 1 measured by Beam 2 detector
- ❑ Problematic: **indistinguishable from real ghosts charge**
- ❑ Solution:
  - ❑ **Detector moved to electronics rack**
  - ❑ Light extracted through **graded-index fiber** to minimize modal dispersion (insufficient light yield with SM-fiber)

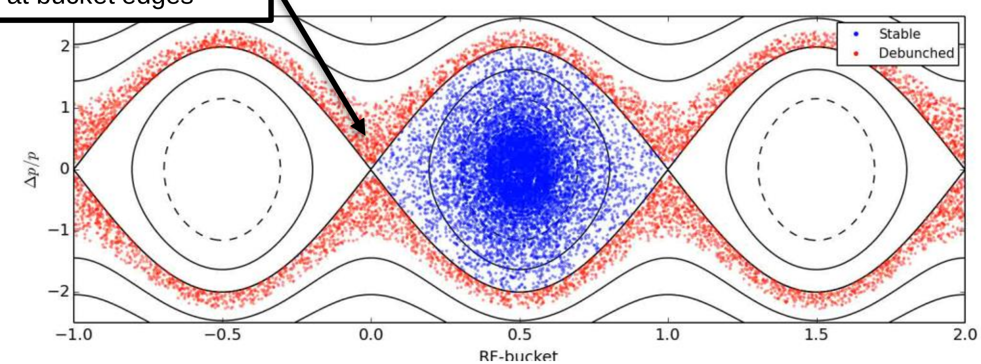




Usability

- BSRL is the only BI instrument that can measure full LHC beam profiles: nominal, satellite and ghosts bunches + debunched beam
- Invaluable for luminosity calibration (ATLAS, CSM, LHCb, ALICE)
- Cross-checking for other instruments (FBCT, Abort Gap monitor, LHCb, …)





- RF-problem during vdM-scan October 2018 ⇒ Continuous “leakage” from filled buckets ⇒ **Debunched protons coasting around ring**
- 5h time-lapse of BSRL measurement

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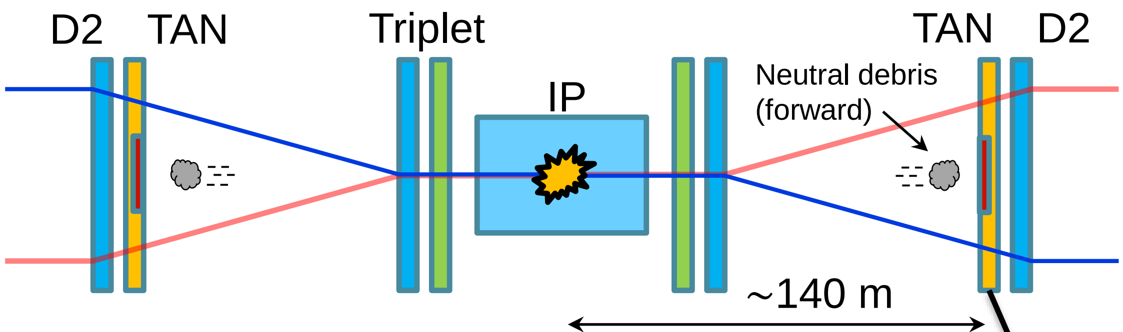
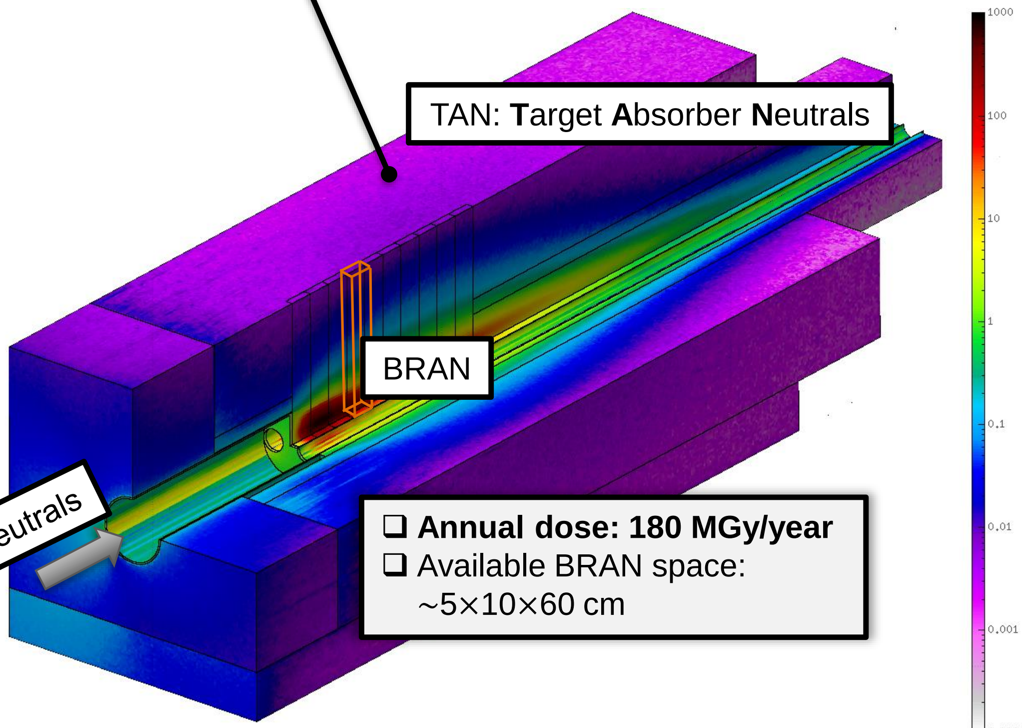
BRAN: Overview



Forward Neutral debris → Absorption in TAN → Charged secondaries

- **BRAN:** Beam RAte of Neutrals
- **Where**: machine luminosity monitors around IP1, IP2, IP5, IP8
- **Why**: Finding collisions, backup instrument for OP (if no data from experiments), cross-check experiments, sanity check, …
- **Precision**: ~1% @ 1 Hz
- **Challenges**:
  - Large dynamic range
  - **IP1 & IP5: radiation**
  - Limited space (50 mm width)
- **HL-LHC**: Cherenkov radiation based monitors

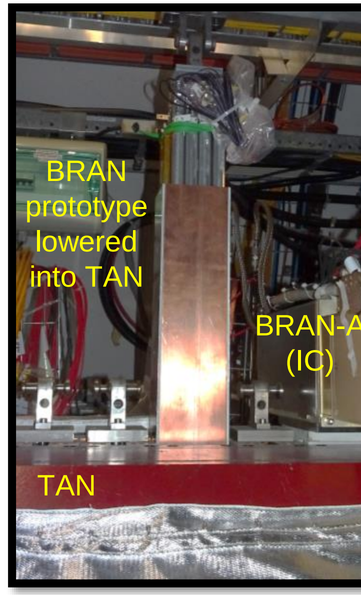


- **Annual dose: 180 MGy/year**
- Available BRAN space: ~5×10×60 cm

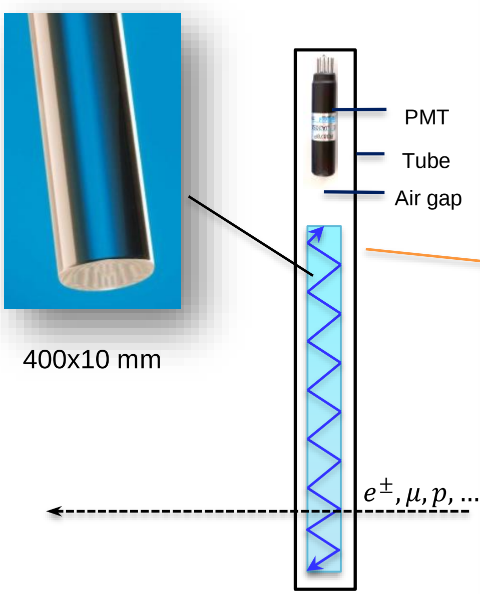
- Minimum Luminosity: **~5E22 cm^{-2}s^{-1}**
  - Grazing Pb-Pb bunch pair
- Maximum Luminosity: **5E34 cm^{-2}s^{-1}**
  - Head-on p-p, full rings

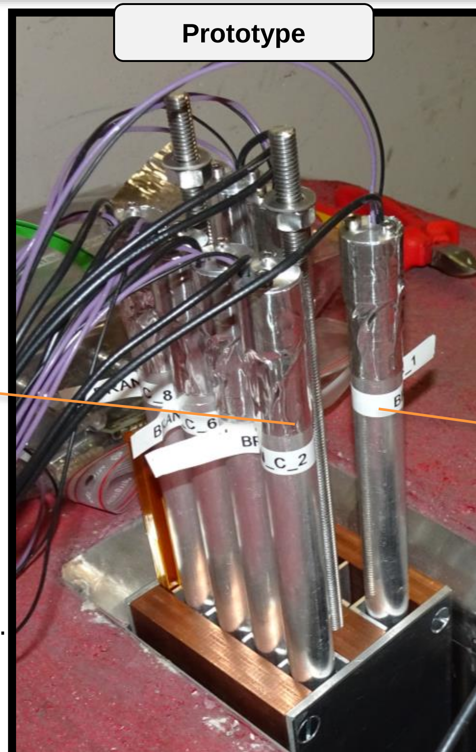
Prototype

- Current BRAN (ionization chambers) is "dying". Last spare amplifier unit was installed a few months ago.
  - New solution needed for HL-LHC
  - Most important: **Robust & Reliable** (hot area → minimal service and interventions)
- New prototype: 2 different Cherenkov media tested
  - **Fused silica** (total internal reflection)
  - **Air** (Aluminum mirror)

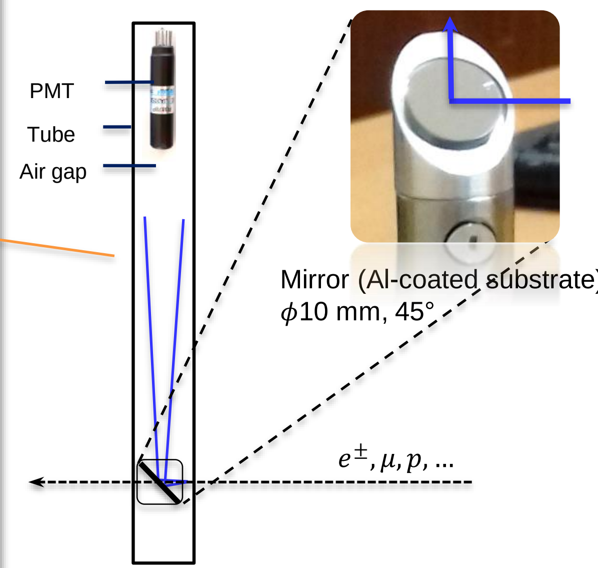


Fused silica rods

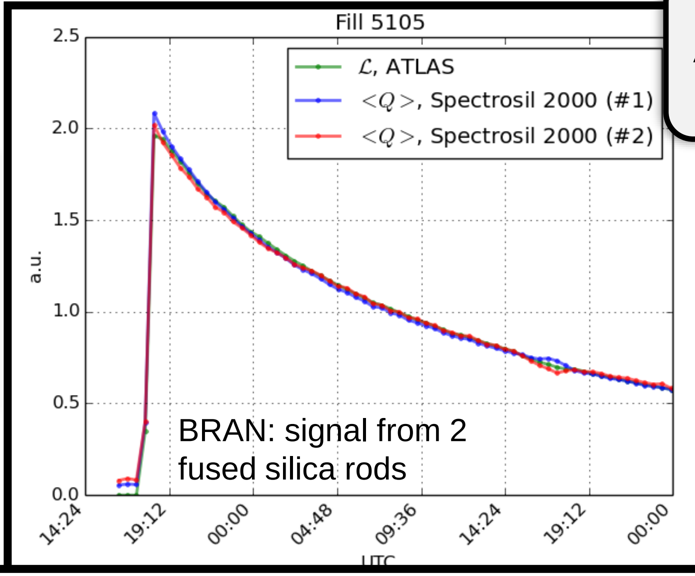




Air + Mirror

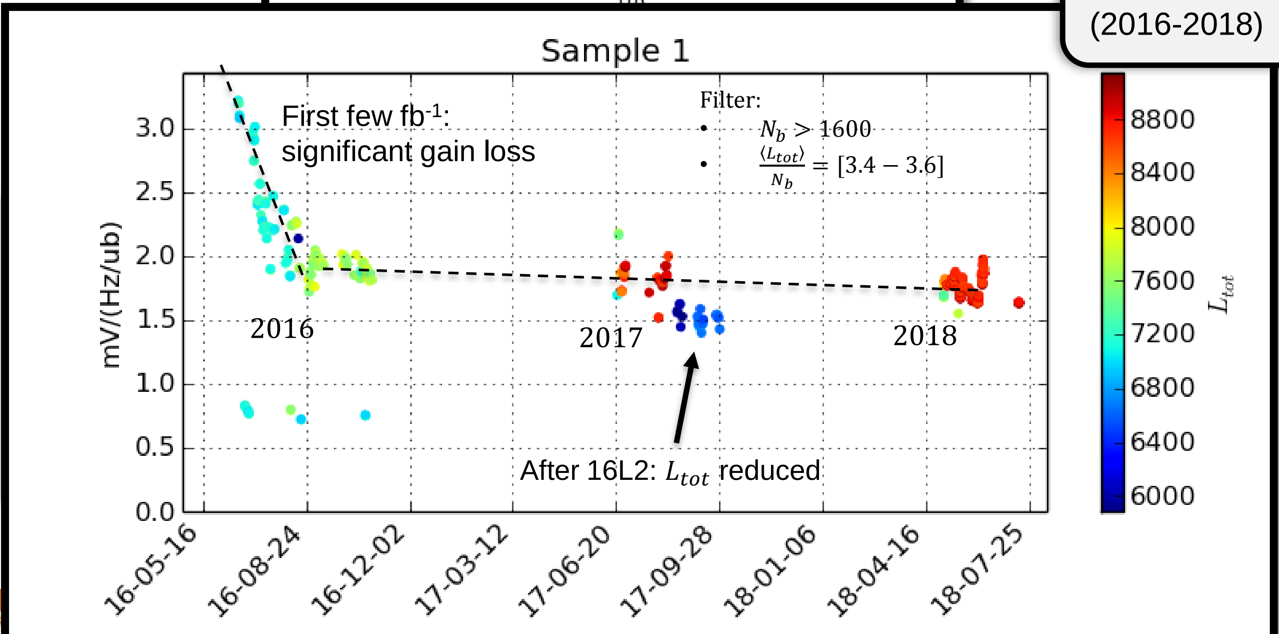


Fused silica



BRAN Signals & ATLAS Luminosity (single fill)

- **Short term (30 h):** Excellent agreement between prototype signal and ATLAS luminosity

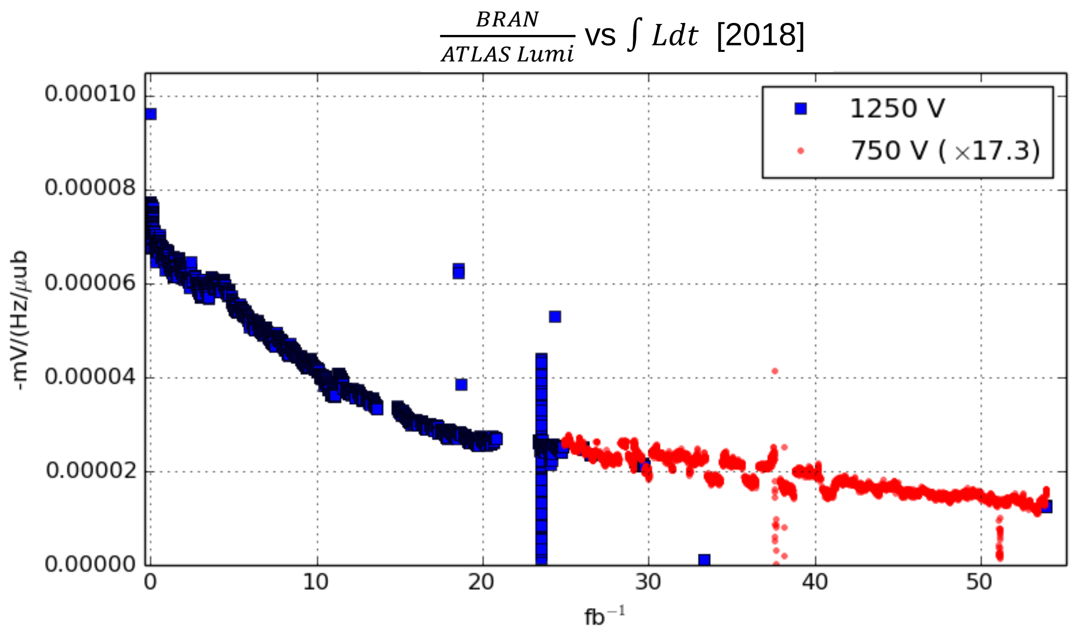


$$\frac{BRAN\ Signal}{ATLAS\ Luminosity}$$ (2016-2018)

- **Long term (3 years):**
- Rapid initial signal loss
- Stable gain from mid-2016 until today!

Aluminum mirrors

- Mirrors at different heights to cope with change in X-ing angle sign



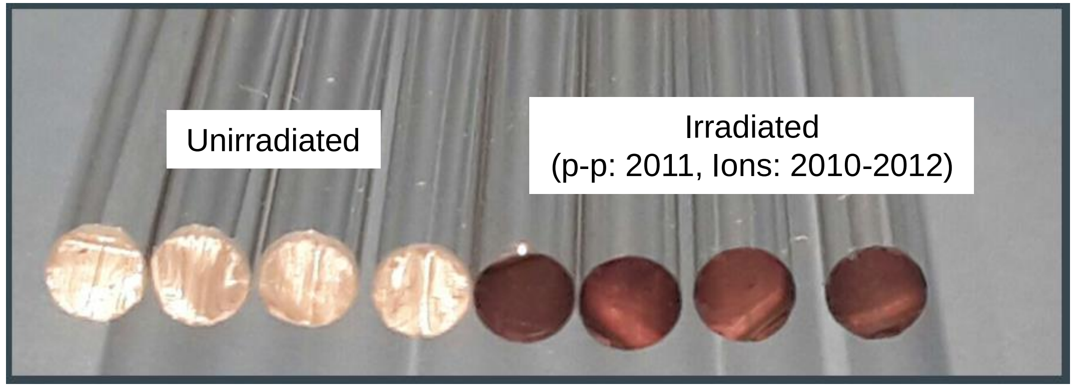
- Mirror with clearest signal also degraded the most
  - Total: **83% loss** in 2018
  - No sign of flattening out…
- Mirror reflectivity to be re-measured after cool down to verify signal loss caused by reduced reflectivity. Other possibilities: reduced reflectivity of stainless steel tube (diffuse)
- **<u>⇒ Fused silica best option</u>**

	Mirror #10	Mirror #11	Mirror #12
Initial gain [compared to quartz rod]	0.6%	2.8%	**8.3%**
Gain loss up to 54 fb^{-1}	-32%	-43%	**-83%**

Radiation damage

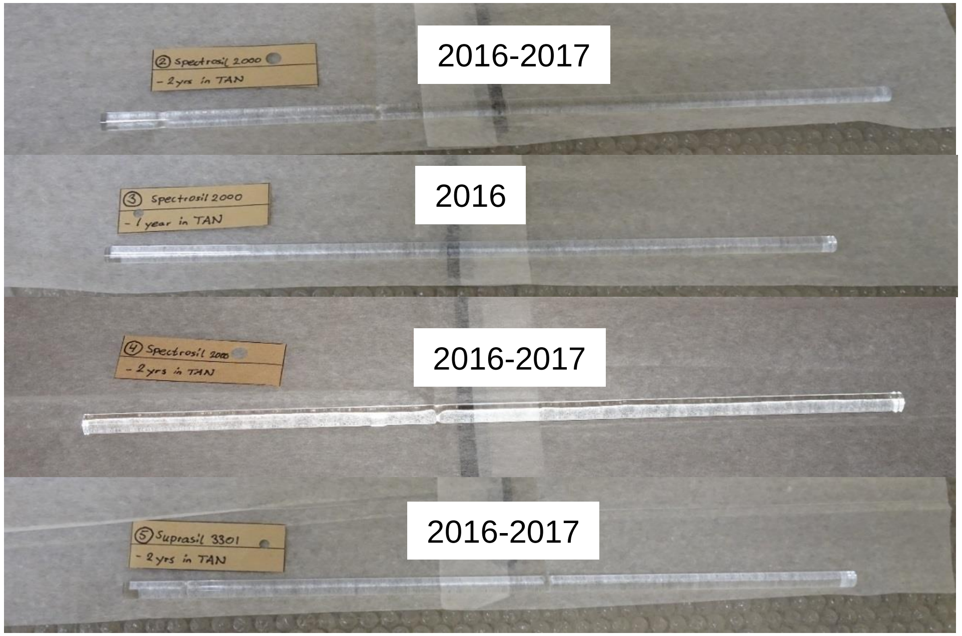
- Main concern: **reduced optical transmission** (=signal loss)
- 4 rods recuperated from TAN after 1-2 years of LHC operation. **No visible discoloration** or opacity (by eye)
- Shipped to ZDC group at University of Illinois for measurements

ZDC Quartz rods



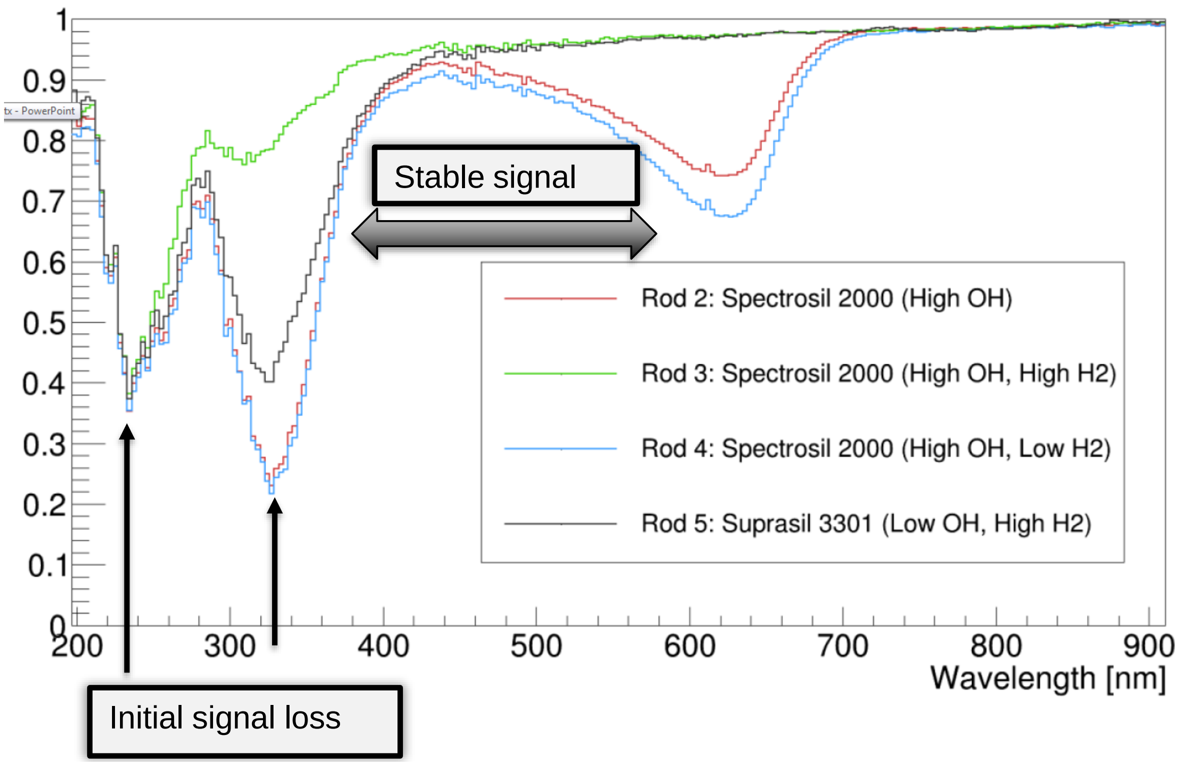
[Courtesy: M. Phipps & G. Avoni]

BRAN Fused silica rods (irradiated)

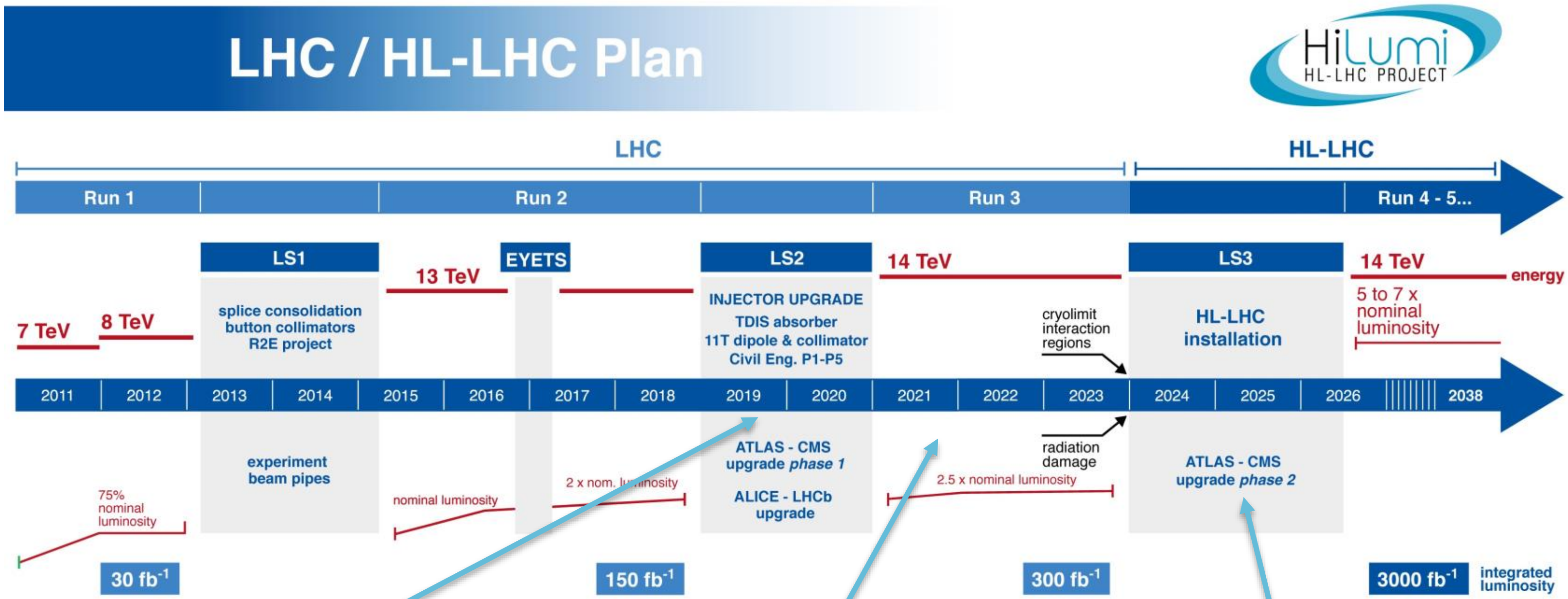


Transmission

- Unirradiated fused silica: very good transmission down to ~180 nm
- Irradiated: Sharp absorption centers in UV range (230 nm, 325 nm)
- Broad absorption around 630 nm
- **400-600 nm largely unaffected**
- Consistent with observations: light yield in visible range guarantees a signal “floor”, even after (very) high dose



Outlook



- ❑ LS2: Replace 2 BRAN-A monitors (ionization chambers) with 2 fused silica BRANs
- ❑ Implement design changes wrt. first prototype

- ❑ Run 3: continued long-term performance evaluation

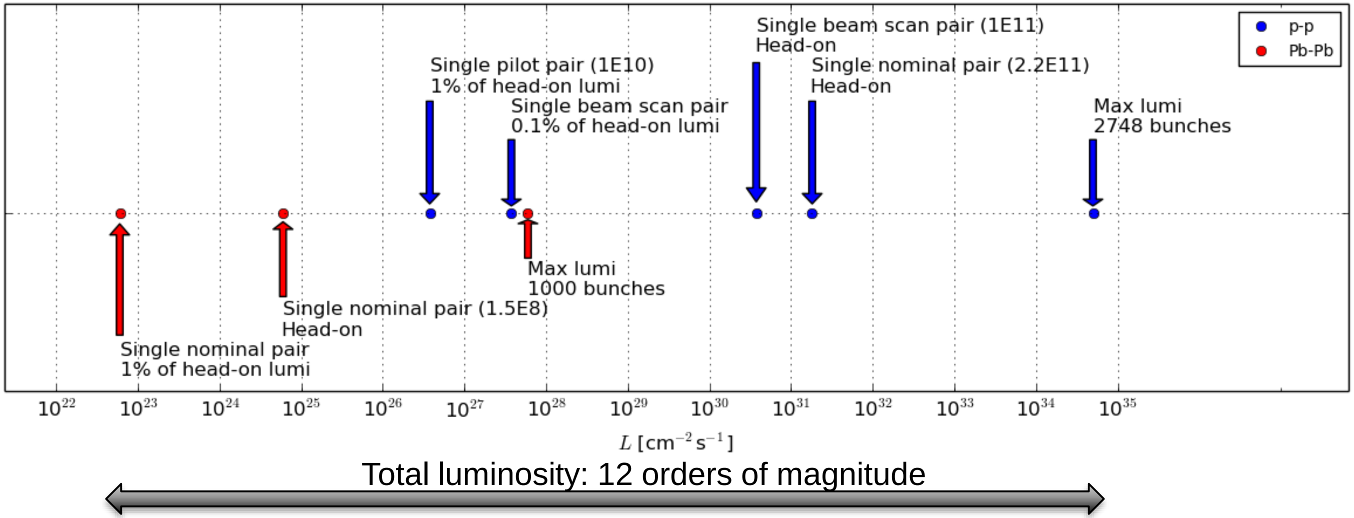
- ❑ LS3: Installation of final HL-LHC BRAN

- Thank you for your attention!

Many thanks to:
- Stephen Gibson, RHUL
- Enrico Bravin, CERN
- Federico Roncarolo, CERN

- Backup slides

Requirements



- ❑ BRAN must measure luminosity over 12 orders of magnitude (single grazing Pb-Pb bunches to head-on p-p with full ring)
- ❑ High annual dose: maintenance difficult due to activation
- ❑ **Robustness** and **reliability** most important design considerations